AFRL-IF-RS-TR-2004-121
Final Technical Report
May 2004

LOCATION-CENTRIC DISTRIBUTED COMPUTATION AND SIGNAL PROCESSING IN MICROSENSOR NETWORKS

University of Wisconsin

Sponsored by
Defense Advanced Research Projects Agency
DARPA Order No. K285

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AFRL-IF-RS-TR-2004-121 has been reviewed and is approved for publication

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	MAY 2004	FINAL Jun 00 – Jun 03

4. TITLE AND SUBTITLE

LOCATION-CENTRIC DISTRIBUTED COMPUTATION AND SIGNAL PROCESSING IN MICROSENSOR NETWORKS

5. FUNDING NUMBERS

G - F30602-00-2-0555
PE - 62302E
PR - K285
TA - 25
WU - C1

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N/A

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10. SPONSORING / MONITORING AGENCY REPORT NUMBER

AFRL-IF-RS-TR-2004-121

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 Words)***

The project addressed the following key challenges in the design of microsensor networks: (1) the need for simple and flexible programming abstraction, (2) the need for energy and bandwidth efficient collaborative signal processing algorithms, and (3) the need for robustness to sensor device failures. To address these challenges, the project developed an approach called location-centric computing. A library of communication primitives was developed based on this approach. These communication primitives were used to build a target tracking application that was robust to a large number of device failures. The associated collaborative signal processing algorithms and the corresponding information fusion algorithms were also developed as part of this project. The effectiveness of the approach and the associated algorithms were demonstrated through network simulations and through experimentation on a sensor network testbed.

14. SUBJECT TERMS

sensors, networks, location-centric computing, routing, tracking, signal processing

15. NUMBER OF PAGES

12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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1. Technical Challenges

In the project proposal, we identified the following three challenges in the design and operation of microsensor networks.

1. **Simple, flexible programming abstraction:** Each sensor device by itself may not be able to provide useful information without collaboration with other devices. At the same time, due to the large ad hoc nature of sensor networks, it is a formidable challenge for a programmer to develop efficient distributed algorithms and implementations without a simple, but flexible, programming model.
2. **Energy and bandwidth optimal distributed signal processing:** Each device is likely to have very limited energy and bandwidth capabilities to communicate with other devices. Therefore, any distributed computation on the sensor network must be very efficient in utilizing the limited power and bandwidth budget of the sensor devices.
3. **Robustness to sensor device failures:** Due to the harsh conditions in which sensor devices may be deployed, and the way in which the devices may be deployed, one can expect a significant fraction of the devices to be either non-operational or malfunctioning. Therefore, the underlying distributed algorithms must be robust with respect to a large number of device failures.

The project goal is to address these challenges. To accomplish this goal, the proposal identified the following three tasks.

Task 1: Software Library of Communication Primitives

- Identify syntax and semantics of a set of communication primitives suited for location-centric distributed computing and signal processing.
- Implement the communication primitives on a network of laptops equipped with wireless interfaces.

Task 2: Multi-resolution Collaborative Signal Processing

- Develop distributed signal processing algorithms for microsensor networks.
- Implement the distributed signal processing algorithms using the software library of communication primitives.

Task 3: Fault-tolerance and Self-testing

- Identify syntax and semantics of communication primitives for incorporating fault-tolerance in microsensor networks.
- Develop built-in-self-test based fault-tolerant extensions of distributed signal processing algorithms.

The following section describes the project accomplishments in each of the three tasks.

2. Project Accomplishments

2.1 Task 1: Software Library of Communication Primitives

- **Communication primitives for location-centric computing:** The project is based on the premise that sensor network applications typically require collaboration among devices in a certain area and not among an arbitrarily specified set of devices. For example, application queries such as what is the concentration profile of a certain bio-chemical agent in a given area, or what is the temperature or pressure variation in a given area, or have there been any unauthorized entries into a given area, all require collaboration among sensor devices in the area of interest as opposed to collaboration among a given set of devices. Note that, this is fundamentally different from the conventional node-centric approach in which the information exchange is between certain set of devices. Even if the devices move, the collaboration typically continues between the same set of devices. In contrast, in a sensor network, a device ceases (begins) to participate in an ongoing collaboration if it leaves (enters) the corresponding defining region. We refer to this new approach for sensor networks as *location-centric computing*.

  We identified a set of communication primitives well-suited for location-centric computing. We also developed the associated application programmers interface called UW-API [12]. In UW-API, geographic regions play the role of a node in the traditional network interface. In particular, the nodes/devices are not individually addressable in UW-API. Instead, the programmer creates entities called regions, which are then addressable in the communication primitives. As described later, these primitives were used to build collaborative signal processing applications for target detection, classification, and tracking.

- **Location-centric routing algorithms:** We developed a routing scheme called UW-Routing that is well-suited for supporting the information exchange required for location-centric computing [12]. The routing scheme utilizes the fact that sensor nodes are usually aware of their location to efficiently deliver messages from one region to another.

- **Software suite for target tracking:** Based on UW-API and UW-Routing we developed a software architecture called UW-Senware for target tracking applications. The architecture was prototyped on Sensoria's WINS2.0 nodes. The prototype contained UW-API, UW-Routing, and the fault-tolerant collaborative signal processing algorithms developed as part of Task 2 and Task 3 thrusts of this project. The prototype also integrated with software developed in other research efforts as part of the SensIT program. In particular, it integrated with BAE Austin's Timeseries Data Repository and Virginia Tech's Graphical User Interface for query submission and visualization of results.

- **Participation at SITEX 02 and Waltham demonstrations:** We demonstrated UW-Senware at 29 Palms US Marine Base in California in November 2001 and at BBN, Waltham in November 2002. At 29 Palms, UW-Senware ran on a network of 15 WINS2.0 nodes. At Waltham, UW-Senware ran on a network of 25 WINS2.0 nodes. From the 29 Palms site, we collected a large amount of data which was used to refine the algorithms not only at Wisconsin but also in several other projects.

2.2 Task 2: Multi-resolution Collaborative Signal Processing

Distributive signal processing algorithms have been developed for the detection, classification, localization and tracking of multiple moving targets within a sensor field.

Specifically, the following key technologies have been developed:

- **Multi-modality, multi-sensor region-based target energy detection algorithm:** We have developed a constant-false alarm rate (CFAR) energy based target detection algorithm for the purpose of detecting the presence of target within the sensor field. This algorithm is capable of performing decision fusion using detection results obtained from multiple sensors with multiple sensing modalities. This algorithm has been implemented in the November 2002 demonstration software.

- **Multi-modality, multi-sensor target classification algorithm:** Acoustic spectral features have been utilized to develop a maximum likelihood based pattern classifier to classify the detected vehicle into specific types. This algorithm has been implemented in November 2002 demonstration software. The results have been reported in a journal paper and submitted to Journal of Parallel and Distributed Computing [7].

  A distance based decision fusion algorithm has been developed that facilitates optimal linear combination of classification results at individual sensor nodes to reach a decision-fused classification result. The initial result is published in 2003 IPSN symposium [20], and a complete result will appear in Journal of Telecommunication Systems in 2004 [8].

- **Acoustic energy based target localization method:** An energy based collaborative source localization algorithm [6], [23] using ratios of acoustic energy measured at neighboring sensors has been developed. This algorithm has been incorporated in the initial release of the UW-CSP software and applied in the demonstration in November 2002. The result has been published in Journal of EUROSIP Applied Signal Processing.

  A closed-form least square estimation method has been developed and compared with existing constrained least square algorithms for target localization applications [6]. The result has been submitted to IEEE Transactions on Signal Processing.

A maximum likelihood target localization method based on acoustic energy measurements on individual sensor nodes has been formulated and developed Initial result has appeared in IPSN2003 proceedings [21], and an enhanced complete result has been submitted to IEEE Transactions on Signal Processing [5].

A suite of collaborative signal processing algorithms for the detection, classification, localization, and tracking has been developed. Special attention has been paid to operating in an unreliable environment. The implementation details of the UW-CSP algorithm have been included in a Masters of Science report **[32].**

- **Interplay between signal processing and information routing:** We developed a statistical signal model for sensor measurements that reveals key principles underlying the interplay between distributed signal processing and information routing in sensor networks [1, 22]. Based on knowledge of spatial bandwidths of the signal field in a query region, the model partitions the region into coherence sub-regions. The model suggests a structure for information exchange between nodes (to enable CSP) that is naturally suited to the communication constraints of the network: high-bandwidth (feature level) information exchange is limited to spatially local nodes within each coherence region, whereas only low-bandwidth (symbol level) information exchange is needed across distant nodes in different coherence regions. This structure on information exchange for CSP naturally complements the location-centric routing framework.

- **Framework for distributed detection and classification:** We have developed a framework for distributed detection and classification that exploits the signal model [2, 16]. We have shown that the optimal classifier averages the node measurements in each coherence region to improve the measurement SNR, whereas it combines local (independent) decisions from different coherence regions to make the final decision. Our results based on SITEX 02 data demonstrate a remarkable advantage of fusing local decisions from different coherence regions: a relatively moderate number of unreliable node decisions (probability of error as high as .2 or .3) can be fused to yield extremely reliable final decisions (probability of error as low as .01). Thus, cheap and unreliable sensors can be made arbitrarily reliable by low-bandwidth information fusion across coherence regions.

2.3 Task 3: Fault-tolerance and Self-testing

The focus of our research in this area has been to develop robustness to sensor device failures, communication failures, and DSP algorithm failures in sensor networks. Further, we assume that the failures can be arbitrary, thus resulting into possible malicious behavior by the failing sensors.

Initially we studied the problem of fault diagnosis using self-test and signature based methods in digital circuits. We developed a method of diagnosis that used variable size signature windows to identify faulty components in a digital circuit. These results appeared in [31].

Parallel to the above work, in the early stages, we studied fault tolerant algorithms for target detection activity in a sensor network. We developed a sensor network model for target detection, fault model for the sensor failures, and target model for target activity. These models were very general and were used, with modifications, to study numerous activities of the targets and various sensor network configurations. We formulated the distributed detection problem in which sensors communicate their observations with other sensors to arrive at a consistent and correct decision. We considered two possibilities for communication of information between sensor nodes, namely value and decision exchanges. For these two possibilities we developed and analyzed value and decision fusion algorithms for the sensor network with and without faults. Analytical as well as simulation model of these algorithms were developed and studied in depth using various signal and noise parameters. We compared the performance of value and decision fusion algorithms and arrived at the following conclusions:

1. Value fusion based algorithms are superior to decision fusion based algorithms if no sensor is assumed to be faulty.

2. In the presence of faulty sensors in a sensor network, both value and decision fusion based methods offer comparable performance but decision fusion based algorithms are preferable for their lower communication overhead.

These results were published in the Fusion 2001 conference [29].

Following the above work, hierarchical value and decision fusion based methods were developed and analyzed. These results are due to appear in a book chapter [13] and in IEEE Transactions on Computers and some of the results were presented at a conference [9,13,24].

With detection algorithms in place we expanded our research to study the sensor deployment problem. The objective of deployment is detection of targets in a sensor field. We first developed a metric to determine quality of a deployment. The metric, namely minimum exposure, can assess the performance of a sensor network in detecting target(s) carrying out various un-authorized activities in a region being monitored by the sensor network. We identified three target activities of interest: idling, reaching, and traversing. We developed and analyzed various methods of deployment. In particular we developed an optimal method for random deployment of sensors and the research results were published in [17, 26].

The conclusion of the above studies was that a sequential deployment strategy is superior in terms of cost of deployment. The above results did not include the presence of obstacles and variations in the speed of target movement. We developed an obstacle model and algorithms to analyze deployments for various speeds of the target motion as well for various target activities [19].

Finally, we developed analysis methods to study the performance of different deployments in the presence of faulty sensors. We developed an efficient algorithm to determine the minimum exposure of a deployment for the "idling" activity of a target and we developed a genetic algorithm based method for the reaching and traversing activities of targets. These results appear in [18].

3. Publications

[1] Ashwin D'Costa, Vinod Ramachandran, and Akbar Sayeed, "Distributed Classification of Gaussian Space-Time Sources in Wireless Sensor Networks," submittted to the IEEE Journal Selected Areas in Communications (special issue on sensor networks), 2003.

[2] Sayeed, "A Statistical Signal Modeling Framework for Integrated Design of Sensor Networks," submitted to the IEEE Signal Processing Magazine, 2003.

[3] Xiaohong Sheng and Yu-Hen Hu, "Maximum Likelihood Wireless Sensor Network Source Localization Using Acoustic Signal Energy Measurements," submitted to IEEE Transactions on Signal Processing, 2003.

[4] T.-L. Chin, T. Clouqueur, P. Ramanathan, and K. K. Saluja, ``Vulnerability of sensor networks to faults, submitted to Dependable Systems and Networks, 2003.

[5] Xiaohong Sheng and Y. H. Hu, "Maximum Likelihood Wireless Sensor Network Source Localization Using Acoustic Signal Energy Measurements," submitted to IEEE Transactions on Signal Processing, 2003 (under revision)

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The following personnel are associated with the research effort

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